Gait Characteristics in Individuals With Intellectual Disabilities

A Literature Review

Running Head: Gait characteristics individuals with ID

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Abstract

Gait is a functionally highly relevant aspect of motor performance. In the general population poorer gait increases the risk of falls and is a predictor for future disability, cognitive impairment, institutionalization and/or mortality. People with intellectual disabilities (ID) show a delayed motor development, which brings to attention the abnormalities that might accompany gait in this population throughout childhood and adulthood. Therefore, this paper aims (a) to provide a focused review of the available literature on gait characteristics in individuals with ID and (b) to gain insight into available instrumentations measuring gait in this population. We searched the database of Pubmed for relevant articles and the reference lists of included articles, resulting in 44 included articles. Forty one studies reported gait characteristics during over-ground walking and six studies during perturbed walking conditions. Most studies investigated syndrome-specific ID populations, only five studies investigated the general ID population. The studies show that gait abnormalities are evident during over-ground walking in the ID population, both in people with genetic syndromes and with ID without genetic syndromes. During perturbed conditions people with ID altered their gait with stability-enhancing adaptations. Abnormalities in gait may be partly explained by physical features, but the interrelatedness between gait and cognition may also be an explanation for the gait abnormalities seen in the ID population. Further research regarding gait characteristics of the ID population, and its relation to cognitive functioning, and adverse health outcomes is needed.

Keywords

Gait, walking, instruments, intellectual disabilities

1. Introduction

Intellectual disability (ID) has been reported by the American Psychiatric Association to have an overall prevalence of approximately 1%, and is defined as “a disorder with onset during developmental period that includes both intellectual and adaptive functioning deficits in conceptual, social, and practical domains” (American Psychiatric Association, 2013). Despite the fact that this definition does not include a direct association to physical and motor functioning of individuals with ID, this topic has been lately given a considerable attention (Blomqvist, Olsson, Wallin, Wester, & Rehn, 2013; Hartman, Houwen, Scherder, & Visscher, 2010; Rintala & Loovis, 2013; Smits-Engelsman & Hill, 2012; Vuijk, Hartman, Scherder, & Visscher, 2010; Westendorp, Houwen, Hartman, & Visscher, 2011)

Delayed motor development is displayed by the children in this population (Molnar, 1978). While it is unlikely that cognition alone is the sole mechanism for the motor delay (Hreidarsson, Shapiro, & Capute, 1983), an association between cognitive and motor performance has been reported (Vuijk et al., 2010; Wuang, Wang, Huang, & Su, 2008). Individuals with lower measured Intelligence Quotient (IQ) more often showed poorer motor performance and needed more time to learn a motor task, than those with a higher measured IQ (Rousey & Eyman, 1995; Smits-Engelsman & Hill, 2012; Westendorp et al., 2011). This conclusion is supported as well by Hartman et al. (2010) who found that executive functioning in children with ID was impaired, and this was interrelated with the motor domain.

An intellectual disability could originate from a range of causes both genetic and environmental, resulting in a very heterogeneous population (Bessa, Lopes, & Maciel, 2012). When ID is associated with a genetic syndrome, there may be characteristic physical features (American Psychiatric Association, 2013). For example, children and adolescents with Down syndrome (DS) exhibit insufficient motor ability (Spanò et al., 1999; Wang, Long, & Liu, 2012). They acquire gross motor skills at a different age than their peers of typical development (TD), with the more complex the skills, the greater the time difference (Pereira, Basso, Lindquist, da Silva, & Tudella, 2013). Furthermore, less functional postural strategy is exhibited in DS over the age continuum (Rigoldi, Galli, Mainardi, Crivellini, & Albertini, 2011), with a worse static and dynamic balance and a wide variability (Villarroya et al., 2012). This trend also extends to older persons with DS as they present poor sensory-motor performance (Carmeli, Ariav, Bar-Yossef, Levy, & Imam, 2012). People with Williams Syndrome (WS), Fragile-X syndrome, and Prader-Willi Syndrome (PWS) also achieve milestones in gross motor skills at a later stage in life (Largo & Schinzel, 1985; Plissart & Fryns, 1999; (Reus et al., 2011). Furthermore, in certain genetic disorders such as Rett syndrome, there are periods of worsening (American Psychiatric Association, 2013), such as losing functional gross motor skills that have been already achieved (Foley et al., 2011; Hanks, 1990; Kerr, 1995).

Both also in children and adults with ID without genetic causes, motor performance seemed to be affected. Functional locomotor skills such as running, hopping, leaping, jumping, and walking were found to be less well developed in the ID population (Hartman et al., 2010; Rintala & Loovis, 2013; Spanò et al., 1999). Previously it was reported that children with ID show a significant delay in the mean age of walking onset compared to their peers of TD, with a later onset of walking with more severe ID (Hreidarsson et al., 1983). Such delayed walking skills bring to attention the abnormalities that might accompany gait in this population throughout childhood and adulthood. Gait is a functionally highly relevant aspect of motor performance, and has been linked to the level of functioning and to morbidity in the general older adult population, where poorer gait not only increased the risk of multiple falls (Callisaya et al., 2011), but also predicted future disability, cognitive impairment, institutionalization and/or mortality (Abellan van Kan et al., 2009). However, the predictive value of gait parameters in the general older population is based on a decline in physical fitness and general functioning during the ageing process, while people with ID experience lifelong levels of low physical fitness (Black, Smith, Wu, & Ulrich, 2007; Golubovic, Maksimovic, Golubovic, & Glumbic, 2012; Hilgenkamp, van Wijck, & Evenhuis, 2012; Lahtinen, Rintala, & Malin, 2007; Oppewal, Hilgenkamp, van Wijck, & Evenhuis, 2013; Salaun & Berthouze-Aranda, 2012) and probably have learned different compensation strategies (Black et al., 2007; Rigoldi, Galli, & Albertini, 2011; Smith, Stergiou, & Ulrich, 2011). This might alter the way gait parameters need to be interpreted in people with ID, for example in relationship to falls. Additionally, next to being a physical function, gait has to be recognized as a cognitive function as well, considering that it involves the integration of attention, planning, memory, and other motor perceptive and cognitive processes (Axer, Axer, Sauer, Witte, & Hagemann, 2010). Slower gait speed is explained by slower information processing in the general older adults population (Rosano et al., 2012). Keeping in mind that individuals with ID are presented with deficits in such cognitive functions, this population may exhibit abnormalities in gait.

Before advancing to studies aiming to answer these interesting and highly relevant questions, it is necessary to determine the current state of the art of this emerging research area. Therefore, this paper aims to provide a focused review of the available literature on gait characteristics in individuals with ID. In addition, this review aims to gain insight into the available instrumentations measuring the different gait parameters in this population.

2. Methods

2.1 Literature Search

A literature search was conducted in the PubMed electronic database in August 2013. Using Intellectual disabilities and Gait as keywords with the combination [(intellectual disability) AND gait]. To be included in this review, all articles had to (a) be published in English, (b) have primary outcome measures in one of the gait parameters categories of spatio-temporal, kinematics, kinetics, dynamic electromyography, and/or energetics, (c) include participants with ID of any age, including the different genetic syndromes resulting in ID. The electronic search was not restricted to a publication date or publication status.

2.2 Data Extraction and Management

Data was extracted from the included studies using an adapted form based on the Cochrane Library Collaboration- Wounds Group data collection Form. Pilot-testing of the developed form was conducted on three randomly-selected included studies, and then modified accordingly. The first author extracted the following data from the included studies:

- Study characteristics including the aim of the study and the study design.
- Population description, inclusion and exclusion criteria, and participant characteristics (age, gender, and level of ID).
- Apparatus or equipment used for measuring gait with the described protocols.
- Statistical analysis.
- Outcome measures as gait parameters with their definitions and scales, if provided.

When in doubt, a second reviewer screened the articles. Two authors were contacted for further information. Both responded and one provided numerical data that has been presented in a table in the published paper. No formal quality assessment was conducted for the included studies; considering the aim of including as many studies as possible to get a comprehensive overview of the available literature. Nevertheless, studies have been read critically, and descriptive information is provided (Table 1) to give the reader the opportunity to assess the quality of the included studies.

Insert figure 1 here

3. Results

As a result, the search yielded a total of 442 articles. Six other articles have been added by the second author through updating emails via PubMed database. The retrieved studies have been screened by titles and abstracts for eligibility, and 401 were excluded. After a full-text screening for the remaining 47 studies, ten articles were further excluded for not meeting the inclusion criteria. A reference list search of the included final 37 articles was conducted, and resulted with another seven articles that met the inclusion criteria. Therefore, the final number of studies included for the review was 44, covering the investigation of gait characteristics in the ID population (Figure 1).

3.1 Descriptives included articles

Forty one studies reported investigating gait characteristics during over-ground walking (Table 1), and six studies reported gait characteristics during crossing obstacles and under different perturbed walking conditions (Table 2) (Hocking et al., 2011; Mulvey, Kubo, Chang, & Ulrich, 2011; Smith, Ashton-Miller, & Ulrich, 2010; Smith & Ulrich, 2008; Sparrow, Shinkfield,

& Summers, 1998; Vimercati, Galli, Rigoldi, & Albertini, 2013). All studies had a cross-sectional design, except for six studies which had a longitudinal design (Accardo & Whitman, 1989; D. Black, Chang, Kubo, Holt, & Ulrich, 2009; Yoichi Chiba & Shimada, 2009; Gontijo et al., 2008; Looper, Wu, Angulo Barroso, Ulrich, & Ulrich, 2006; Rigoldi, Galli, Mainardi, et al., 2011).

Thirty nine studies investigated syndrome-specific intellectual disability populations, of which thirty six were in Down syndrome (DS), two in Prader-Willi Syndrome (PWS), and three in Williams Syndrome (WS). Gait characteristics in the general ID population have been reported in five studies (Accardo & Whitman, 1989; Chiba et al., 2009; Haynes & Lockhart, 2012a; Ohwada, Nakayama, Suzuki, Yokoyama, & Ishimaru, 2005; Sparrow et al., 1998).

The studies covered a wide range of ages, starting from 17.5 months till 69 years. There is no major dominance of trend between the number of studies investigating children (n = 16) or the ones in the adult population (n = 22). However, only three studies reported about adults over the age of 50 years (Chiba et al., 2009; Smith et al., 2010; Smith, Stergiou, & Ulrich, 2011). Only seven studies reported the level of ID of the participants (Chiba et al., 2009; Haynes & Lockhart, 2012; Hocking, Rinehart, McGinley, & Bradshaw, 2009; Marchewka & Chwala, 2007; Ohwada, Nakayama, Suzuki, Yokoyama, & Ishimaru, 2005; Sparrow et al., 1998; Vimercati et al., 2013).

The following section will present gait characteristics under two main headings, (1) over-ground walking and (2) walking over obstacles and under perturbed conditions. Over-ground walking will be categorized into the different parameters of gait including, spatio-temporal parameters (distance-related and time-related parameters), kinematics (motion curves, joint angles, angular velocities), kinetics (forces, moments, power), dynamic electromyography (muscle activity), and energetic costs (Perry, 1992; Sutherland, 2002, 2005).

3.2 Over-ground walking

3.2.1 Spatio-temporal gait parameters

Thirty two studies reported measuring spatio-temporal gait parameters using different methods. The GAITRite electronic walkway was mostly used to measure spatio-temporal gait parameters at preferred or self-selected walking speed (Horvat et al. 2013; Horvat et al., 2012; Looper et al, 2012; Smith et al., 2011; Mulvey et al., 2011; Hocking et al., 2010; Black et al., 2009; Hocking et al., 2009; Smith & Ulrich, 2008; Smith et al., 2007; Kubo & Ulrich, 2006; Looper et al., 2006; Buzzi & Ulrich, 2004; Ulrich et al., 2004; and Gretz et al. 1998). A treadmill was mostly used to assess gait for slower and faster speed conditions. A three dimensional optoelectronic gait analysis system was also repeatedly used to measure spatio-temporal parameters. Pedralli & Schelle (2013) used an adapted carbon paper method (Table 1).

In DS, compared with their peers of TD, lower values for gait cycle time, percent of swing, step length, stride length, gait speed, and cadence have been reported (Cimolin et al., 2010; Galli, Rigoldi, Brunner, Virji-Babul, & Giorgio, 2008; Hocking, McGinley, Moss, Bradshaw, & Rinehart, 2010; Horvat, Croce, Zagrodnik, Brooks, & Carter, 2012; Mulvey et al., 2011; Rigoldi, Galli, & Albertini, 2011; Rigoldi et al., 2012; Smith et al., 2010; Smith & Ulrich, 2008). Meanwhile, Horvat et al. (2013) found a higher step length and stride length. Both Smith et al. (2007) and Ulrich et al. (2004) found a higher cadence in DS. Higher step width, stride width, base of support, percent of stance in the gait cycle, percent of double support in the gait cycle, double support time, and stance time were found in DS (Cimolin et al., 2010; Darren R

Hocking et al., 2010; Horvat et al., 2013, 2012; Mulvey et al., 2011; Rigoldi, Galli, & Albertini, 2011; Rigoldi et al., 2012; Smith et al., 2011, 2010, 2007; Smith & Ulrich, 2008; Ulrich et al., 2004). However, Gretz et al. (1998) reported lower values for step time in a group of adults with DS, and Horvat et al. (2013) reported lower values for stride width and double support time. Step width has also been reported to be lower in DS by Horvat et al. (2012). The Approximate Entropy (ApEn) was used to quantify the regularity of the patterns observed in size of successive step widths and step lengths in DS. Smith et al. (2011) showed that preadolescents with DS had higher ApEn values compared to new walkers and adults with DS; indicating a less regular pattern which might be more adaptable (i.e. ability to use higher amounts of variability in an adaptive way). Buzzi & Ulrich (2004) have also reported that preadolescents with DS had higher ApEn values at the thigh and foot segments in particular than peers of TD. Which support the same conclusion of a less regular pattern previously stated by Smith et al. (2011).

In PWS, compared with their peers of TD, higher percent stance of gait cycle has been reported (Cimolin et al., 2010; Vismara et al., 2007). Lower values for single support as a percentage of gait cycle, step length, stride length, cadence, and gait speed have been reported in comparison with peers of TD (Cimolin et al., 2010; Vismara et al , 2007).

In WS, compared with their peers of TD, Hocking et al. (2010, 2009) reported higher values for base of support, double support as a percent of the gait cycle, and cadence in preferred, slow, and fast walking speeds. Meanwhile, lower values for speed and stride length have been found (Hocking et al., 2010, 2009).

In the general ID population, compared with their peers of TD, lower values of gait speed and step length have been reported (Haynes et al., 2012; Chiba et al., 2009). However, Sparrow et al. (1998) found a higher gait speed and higher cadence, and lower values for stride length and stride duration in both males and females with ID compared to peers of TD. Additionally, the presence of toe walking was reported to be evident in 35.8% of subjects with ID, investigated in a longitudinal study by Accardo & Whitman (1989).

3.2.2 Kinematic gait parameters

Fourteen studies reported kinematics gait parameters (Buzzi & Ulrich, 2004; Cimolin et al., 2010; Galli et al., 2008; Gretz et al., 1998; Haynes & Lockhart, 2012; Kim, Bang, & Kim, 1995; Parker & Bronks, 1980; Pedralli & Schelle, 2013; Rigoldi, Galli, & Albertini, 2011; Rigoldi, 2009; Rigoldi et al., 2012; Smith et al., 2011; Vismara et al., 2007). Such data have been obtained in motion laboratories using a 3D Gait analysis system, comprising of optoelectronic systems, video recording, and passive reflective markers attached to specific anatomical landmarks on the participants' body. Kinematic measurements are collected for each joint in all three cardinal planes of motion.

In DS, compared to their peers of TD, higher mean values of pelvis tilt and range of motion of the pelvis in the sagittal plane and frontal plane have been found (Cimolin et al., 2010; Kim et al., 1995; Rigoldi et al., 2012). In the hip joint, compared with peers of TD, higher values were reported for the angle at initial contact in the sagittal plane, higher values for minimum of hip flexion in stance, higher values for maximum hip extension in stance and higher hip range of motion in the frontal plane (Cimolin et al., 2010; Galli et al., 2008; Rigoldi, Galli, & Albertini, 2011; Rigoldi et al., 2012). Meanwhile, lower values were found for the hip flexion extension range of motion in the sagittal plane. The knee joint values have been reported to be higher for the angle at initial contact in the sagittal plane in DS than in their peers of TD (Galli et al., 2008;

Rigoldi et al., 2012), but lower by Cimolin et al. (2010). Higher values were found in the knee minimum flexion during stance in DS, and lower values for the knee flexion extension range of motion and the maximum knee flexion during the swing phase (Cimolin et al., 2010; Rigoldi, Galli, & Albertini, 2011; Rigoldi et al., 2012). For the ankle joint kinematics in DS compared with their peers of TD, lower values have been found for the ankle angle at initial contact in the sagittal plane and the ankle dorsi-plantarflexion range of motion. Additionally, lower values have been found for the maximum ankle dorsiflexion during stance and during swing, and for plantar flexion during terminal stance (Cimolin et al., 2010; Galli et al., 2008; Rigoldi, Galli, & Albertini, 2011; Rigoldi et al., 2012). Kim et al. (1995) reported a greater external rotation of the foot in DS compared to their peers of TD. For the shoulder joint, Rigoldi et al. (2011) found a higher range of motion in the frontal plane while walking, for children, teens, and adults with DS compared to peers of TD.

To quantify the local stability of trajectories of knee movement across strides, the Lyapunov Exponent (LyE) calculations have been used in DS, based on continuous kinematic data. Higher values of LyE have been found in the gait pattern of preadolescents with DS compared to new walkers and adults with DS; indicating less stability and possibly a more adaptable gait (Smith et al., 2011). These higher values have been observed as well in comparison with peers of TD, for the preadolescents with DS for the leg segments of shank, thigh, and feet (Buzzi & Ulrich, 2004).

Rigoldi et al. (2009) found a strong relationship between gait quality and cerebellar vermis volume reduction in DS, and also between asymmetrical gait and grey matter volume reduction of some cerebral areas.

In PWS, compared with their peers of TD, higher values have been found for the pelvis tilt and higher hip flexion angle at initial contact in the sagittal plane, higher minimum of hip flexion in stance, and higher hip flexion extension range of motion (Cimolin et al., 2010; Vismara et al., 2007). For the knee joint, higher values for the angle at initial contact in the sagittal plane were found (Cimolin et al., 2010). Meanwhile, lower values were reported for the knee flexion extension range of motion, lower minimum of knee flexion in stance, and lower maximum of knee flexion in swing (Cimolin et al., 2010; Vismara et al., 2007). In the ankle joint of PWS, compared with their peers of TD, lower values were reported for the ankle angle at initial contact in the sagittal plane, lower values for the maximum and minimum ankle dorsi-flexion during stance, and lower ankle dorsi-planter flexion range of motion (Cimolin et al., 2010; Vismara et al., 2007). However, the maximum of ankle dorsi-flexion during swing was found to be higher in PWS than in peers of TD (Cimolin et al., 2010)

For kinematics, Haynes et al. (2012) found that people with ID had higher values for knee angles at initial contact than peers of TD, after accounting for group differences in walking speed. No differences were found in ankle angles at initial contact.

3.2.3 Kinetic gait parameters

Ten studies reported measuring kinetic gait parameters (Cimolin et al., 2010; Cioni et al., 2001; Galli et al., 2008; Gontijo et al., 2008; Kim et al., 1995; Rigoldi, Galli, & Albertini, 2011; Rigoldi et al., 2012; Vismara et al., 2007; Wu & Ajisafe, 2013). The reported studies within these parameters were only in the DS and the PWS populations, using treadmills or force-plates.

Compared with peers of TD, a higher first ankle peak force and a lower second ankle peak force have been reported in DS (Cioni et al., 2001; Wu & Ajisafe, 2013). A decreased ankle generated power and ground reaction force in both medio-lateral and anterior-posterior plane have been found in DS compared with peers of TD (Galli et al., 2008; Kim et al., 1995; Rigoldi, Galli, & Albertini, 2011; Rigoldi et al., 2012). Gontijo et al. (2008) reported a higher gravitational torque at both stance and swing phases of gait for a group of new walkers with DS, over the period of 90 days from walking onset, in comparison with peers of TD.

In PWS compared with peers of TD, lower peak of plantar-flexion moment, and lower values of peak of ankle-generated power have been found by Vismara et al. (2007). The maximum ankle power during the terminal stance in PWS was found to be higher than peers of TD (Cimolin et al., 2010).

3.2.4 Dynamic Electromyography gait parameters

The electrical activity of six muscles from toddlers with DS were recorded, using electro-myography (EMG); to compare the longitudinal changes in the muscular co-contraction (Gontijo et al., 2008). Differences between DS and peers of TD in the co-contraction were observed only for the swing phase of gait, and there was a progressive decrease in the muscular co-contraction with time.

3.2.5 Energetic costs of walking

Ohwada et al. (2005) reported a higher oxygen consumption and higher heart rate during walking at different speeds in individuals with ID than peers of TD. For individuals with DS, Agiovlasitis, Motl, Fahs, et al. (2011) reported higher gross (i.e. overall) metabolic rate (MR), net-MR (i.e. gross minus the value of quiet standing), and higher net energetic cost compared to peers of typical development. In addition, individuals with DS had higher gross-oxygen uptake, higher net-oxygen uptake, and higher net oxygen uptake per kilometer, suggesting that they are less economical during walking than peers of typical development (Agiovlasitis, A.McCubbin, Yun, J.Pavol, & J.Widrick, 2009; Agiovlasitis, Motl, Ranadive, et al., 2011). This is also reported by Mendonca, Pereira, Morato, & Fernhall (2010) for speeds faster than their preferred walking speed.

3.2.6 Other gait parameters

Angular impulse, global stiffness, hip stiffness, ankle stiffness, and center of mass (COM) have been investigated with regard to gait patterns in individuals with DS and PWS (Agiovlasitis, McCubbin, Yun, Mpitsos, & Pavol, 2009; D. P. Black, Smith, Wu, & Ulrich, 2007; Cimolin et al., 2010; Galli et al., 2008; Rigoldi et al., 2012; Ulrich et al., 2004). The general patterns of the COM three-dimensional motion across strides were similar in adults with DS and their peers of TD. But the COM motion in the medio-lateral direction was greater in DS; reflecting greater difficulties with balance during gait (Agiovlasitis, McCubbin, et al., 2009)

Ulrich et al. (2004) reported that children with DS generated higher levels of angular impulse when walking over-ground at comfortable speeds than peers of TD. This has been interpreted in terms of increased global stiffness and both knee and ankle joint stiffness, that are also seen in this population (Cimolin et al., 2010; Galli et al., 2008; Rigoldi et al., 2012; Ulrich et al., 2004).

3.3 Walking over obstacles and perturbed gait

Six studies have reported gait characteristics in walking over obstacles and under perturbed conditions (Hocking et al., 2011; Mulvey et al., 2011; Smith et al., 2010; Smith & Ulrich, 2008; Sparrow et al., 1998; Vimercati et al., 2013).

3.3.1 Obstacle crossing

- Approaching phase

People with ID tended to move quickly when approaching the obstacle and then considerably slowed down after crossing it (Sparrow et al., 1998). While approaching an obstacle, adults with DS showed a slow decrease in percent stance phase throughout their approach, while their peers of TD adjusted their stance phase when they got close to the obstacle, indicating an earlier onset of a stabilizing strategy to cross obstacles (Smith & Ulrich, 2008). In addition, adults with DS shortened their step length while approaching compared with peers of TD (Hocking et al, 2011). While approaching the obstacle, toddlers with DS showed a decrease in step length, an increase in step width, and a decrease in step velocity when compared to the no obstacle condition (Mulvey et al., 2011). The same applies for young adults with DS, who displayed higher variability, lower values of step length, and reduced velocity in the approach phase (Vimercati et al., 2013).

- Lead foot

Lead foot crossing times were earlier in people with ID than in peers of TD, indicating that they completed 80% of the gait cycle in significantly less time (Sparrow et al., 1998). In DS, young adults elicited higher elevation of the lead foot compared to normal walking while crossing the obstacle, which provides larger clearance (Vimercati et al., 2013).

- Trail foot

Meanwhile people with ID allowed significantly less time and distance for the trail foot to traverse an obstacle (Sparrow et al., 1998). In WS, adults tended to reduce their speed and step length at the trail step when compared to controls of TD. In DS, adults revealed longer step duration relative to controls of TD (Hocking et al., 2011).

3.3.2 Perturbation conditions

Twenty eight adults, 14 with DS and 14 with TD, ages 35-65 years have been tested under perturbation conditions including divided attention with counting while walking, distracting sounds by playing street corner sounds, irregular surface, low light condition, and with two combination conditions (counting while walking/low light condition and irregular surface/distracting sounds). Adults with DS demonstrated larger step widths and slower stride velocity than adults with TD, indicating maintenance of stability-enhancing adaptations (Smith et al., 2010)

4. Discussion

This study provides a focused review of the available literature on gait characteristics of individuals with intellectual disabilities (ID), and the used instrumentations to measure these characteristics. The results show that gait abnormalities are evident in the ID population both in people with genetic syndromes and with ID without genetic syndromes. This is in line with a previous review of Enkelaar et al. (2012) about balance and gait capacities of people with ID (Enkelaar, Smulders, van Schrojenstein Lantman-de Valk, Geurts, & Weerdesteyn, 2012).

Spatio-temporal parameters were frequently measured, kinematics had less attention, while kinetics were only reported in a few studies in Down syndrome (DS) and Prader Willi syndrome (PWS), and electromyography (EMG) was limited to one study. Several studies, mainly in DS and one in males with ID without genetic syndromes, measured the energetic cost of walking.

The ID population is widely heterogeneous; therefore different explanations for gait abnormalities are available. These explanations cover physical characteristics and cognitive components. Physical characteristics have been given a considerable attention in the literature, especially in people with ID with genetic syndromes. For example in DS, hypermobility, due to ligament laxity and muscle hypotonia, have an important biomechanical effect on the gait pattern, which may explain the gait abnormalities seen in DS (Galli et al., 2008; Horvat et al., 2012; Rigoldi, Galli, & Albertini, 2011; Rigoldi et al., 2012). In PWS, a decreased gait speed, reduced step length, wider base of support, in addition to higher mediolateral shifting of the COM, and maintaining a forward tilt pelvis were seen, possibly explained by severe obesity, low muscle strength, hypotonicity and small feet (Vismara et al., 2007). All these parameters indicate a cautious gait that aims at maintaining stability during walking.

Since gait abnormalities are seen in people with ID with no specific syndromes as well, the specific physical features do not explain all of the gait abnormalities of the ID population. An alternative explanation is the interrelatedness of gait and cognition. In the general older adult population, the relationships between gait and cognition have been investigated for both people with normal cognition and impaired cognition, and it has been found that poor cognition leads to gait disturbances in the general older adult population (Watson et al., 2010). Interventions targeting cognition may improve gait performance (Montero-Odasso, Verghese, Beauchet, & Hausdorff, 2012). Verlinden, van der Geest, Hofman, & Ikram, (2013) found that cognition and gait show a distinct pattern of association in the general older adults population, with a better global cognition to be associated with better global gait. For specific cognitive domains, it has been found that information processing speed was associated with temporal gait variables; while executive function was associated with spatial gait variables. Holtzer, Verghese, Xue, & Lipton, (2006) concluded that the executive attention, memory, and verbal IQ factors were all related to gait speed. Gait abnormalities such as increased gait variability and decreased gait speed have also been associated with cognitive decline, mild cognitive impairment and Alzheimer’s disease in the general older adults population (Amboni, Barone, & Hausdorff, 2013).

The cognitive components’ relation with gait in ID, has been studied with dual tasks, crossing obstacles, or under perturbed conditions, that have an additional cognitive challenge next to the walking task itself (Axer et al., 2010). During these conditions, it has been found that participants adapted their gait with stability-enhancing adaptations, such as reduction in speed, and increases in step width and step length. So far, this cognitive component has received little attention in the research of gait abnormalities in people with ID.

Next to the risk of falling, the main disadvantage of gait abnormalities from any cause is that they force the individual to expend more energy (Chambers & Sutherland, 2002). Mechanisms related to patterns of gait, such as hip extension, step width, and cadence, have been found to be related to the energy cost of walking in the general older population with slow and variable gait (Wert, Brach, Perera, & VanSwearingen, 2010). This has also been evident in this review for the ID population, as the altered gait pattern forced higher oxygen consumption and increased heart rate, resulting in a less economical walk.

Walking under perturbation and crossing obstacles, adds an additional stress on the different cognitive abilities. This condition forces the brain to deal with more than walking as a single task, and as a result, changes in the gait parameters, such as reducing speed, can be the way to prioritize one task over another. In the general older adults population with mild cognitive impairment and with Alzheimer’s disease or dementia, it has been found that these conditions further worsen gait. Considering that they exhibit certain impairments of specific cognitive domains depending on their form of dementia, cognitive impairment and gait abnormalities often coexist (Amboni et al., 2013).

This review had several limitations. We did not assess the quality of the included articles, which mainly had small sample sizes, low statistical power, and limited generalizability. However, we did not want to apply any kind of formal weighing and selective procedures in appreciating the results, in order to be able to include as many articles as possible. In addition, the electronic search has been conducted only in one search database. However, reference lists of the selected articles were searched for relevant articles, to limit the number of missed articles.

Based on the findings of this review and given the increased longevity experienced by the ID population (McCallion & McCarron, 2004), investigating gait characteristics in the older ID population is worthwhile, since it has been well established in the general older adults population, that higher age is associated with worse gait (Verlinden et al., 2012). Gait speed is an indicator of the health of an older person, as it has been associated with survival in the general older adults population (Studenski et al., 2011). In addition, gait quality has been strongly associated with falls in the general older adult population. Since falls are reported to be the main cause of injury in the ID population with a high prevalence of 10.4% for fall-related injuries, excluding epilepsy-related falls (Finlayson, Morrison, Jackson, Mantry, & Cooper, 2010), this indicates the importance of investigating gait in the ID population.

Reporting differences in gait parameters based on different levels of cognitive functioning would be of value, especially with reporting the compliance of the participants to the testing procedure. Deeper investigation of the relationship of specific cognitive domains with gait characteristics in the ID population is needed, as it can be an indicator to identify subjects with ID that are at risk of falling and decline in functioning. Finally, more research on the validity and reliability of the different instrumentations for gait analysis used in the ID population is needed.

Conflicts of interest

none

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Table 1. Gait characteristics in intellectual disabilities (ID) unobstructed over-ground level walking.

Study	Design	Population	N	Age	ID level	Sex M/F		Outcome measures	Results ID *M(SD)*	TD *M(SD)*
Horvat et al (2013)	Cross-sectional	DS	24	(18-28) yrs	N/A	N/A	S.T.	**Preferred walk**		
			12DS					Step length (cm)	67.28(6.39)	53.12(10.11)
			12 TD					Step width (cm)	67.95(6.33)	55.25(9.26)
								Stride length (cm)	134.70(12.82)	106.64(64)
								Stride width (cm)	9.02(1.36)	13.562(5.25)
								Velocity (s)	129.51(1053)	95.4(21.67)
								Single leg support time (s)	0.40(0.02)	0.40(0.04)
								Double leg support time(s)	0.24(0.02)	0.31(0.13)
								Step time(s)	0.52(0.02)	0.56(0.09)
Pedralli & Schelle (2013)	Cross-sectional	DS	9 DS	25.4± 13.5	N/A	5/14	S.T.	Step length (cm)	46.9 (6.8)	N/A
								Stride length (cm)	92.9 (13.7)	
								Gait Cadence(step/sec)	1.9 (0.19)	
								Speed (m/sec)	0.75 (2.6)	
								Base of support (cm)	8.6 (2.9)	

							K.	Foot angle (^{o})	4.9 (8.1)	
Wu & Ajisafe (2013)	Cross-sectional	DS	20	7-10 yrs	N/A		Kn.	**Slow speed (75%OVG)**		
			10DS			8/2		%stance		
			10 TD			8/2		First peak force	29.2	23.7
								Minimal force	50.8	45.5
								Second peak force	67.7	75.2
								Fast Speed(100% OVG)		
								%stance		
								First peak force	23.4	21.4
								Minimal force	51.6	48.0
								Second peak force	71.4	77.8
Haynes et al. (2012)	Cross-sectional	ID	30		1 mild		S.T.	Walking Speed (cm/ sec)	61.7 (21.2)*	137.2 (15.1)
			15 ID	38.5 ± 10.0	4 mod.	11/4		Step Length (cm)	51.4 (14.5)*	76.5 (7.2)
			15 TD	39.2± 10.4	7 sev.	11/4		Heel contact velocity (cm/sec)	72.7 (35.2)	94.5 (23.0)
					4 Prof.					
							K.	Knee angle (^{o})	15.7 (10.4)	9.6 (7.9)
								Ankle angle (^{o})		

									12.1 (8.7)	10.6 (3.5)
Horvat et al. (2012)	Cross-sectional	DS	24		N/A		S.T.	Preferred walk		
			12 DS	22.75 ± 3.05		N/A		Base of support (cm)	12.32 (5.71)	7.78 (2.94)
			12 TD	22.50 ± 3.18		N/A		Step Length (cm)	51.34 (8.79)*	67.00(6.21)
								Step width (cm)	53.79 (8.04)*	67.67 (6.15)
								Stride length (cm)	103.01(17.63) *	134.19 (12.52)
								Stride width (cm)	14.06 (5.21)	8.97 (1.39)
								Toe in/toe out (^{o})	3.79 (7.15)	1.57 (9.95)
								Velocity (normalized)	93.50 (23.82)*	126.05(13.93)
								Single support time (sec)	0.41 (0.04)	0.41 (0.02)
								Double support time (sec)	0.32 (0.13)	0.32 (0.03)
								Stance time (sec)	0.73 (0.16)	0.66 (0.04)
								Step time (sec)	0.53 (0.09)	0.53 (0.03)
								Swing time (sec)	0.40 (0.04)	0.41 (0.02)
							S.T.	Fast walk		
								Base of support (cm)	11.64 (4.42)	8.43 (2.78)
								Step Length (cm)		

								Step width (cm) Stride length (cm) Stride width (cm) Toe in/toe out (⁰) Velocity (normalized) Single support time (sec) Double support time (sec) Stance time (sec) Step time (sec) Swing time (sec)	58.79 (12.44)* 60.79 (12.02)* 118.19(25.03) * 12.99(4.21) 2.05 (8.02) 143.79(50.40) * 0.36 (0.13) 0.28 (0.39) 0.65 (0.53) 0.51 (0.34) 0.37 (0.13)	82.41 (9.17) 83.01 (9.23) 165.11(18.36) 9.31 (1.67) 0.72 (3.56) 197.78(28.01) 0.35 (0.03) 0.14 (0.03) 0.49 (0.05) 0.42 (0.04) 0.35 (0.03)
Looper et al. (2012)	Cross-sectional	DS	6 DS	(4-7yr.)	N/A	N/A	S.T.	**Barefoot** Step length (cm) Stride length (cm) Base of support (cm) Single support time (sec) Velocity (cm/sec)	 40.80 (6.99) 82.17 (14.00) 10.42 (2.62) 0.32 (4.04)	N/A

Cadence (steps/min)	122.64 (31.81)
Cycle time (sec)	178.09 (31.56)
Surestep Orthoses	
Step length (cm)	0.69 (0.13)
Stride length (cm)	
Base of support (cm)	41.17 (4.19)
Single support time (sec)	83.08 (8.67)
Velocity (cm/sec)	10.38 (2.77)
Cadence (steps/min)	0.33 (0.03)
Cycle time (sec)	110.82 (23.97)
Foot Orthoses	
Step length (cm)	159.90 (28.22)
Stride length (cm)	0.78 (0.12)
Base of support (cm)	
Single support time (sec)	43.19 (4.11)
Velocity (cm/sec)	86.89 (8.00)
Cadence (steps/min)	11.26 (2.85)
Cycle time (sec)	0.32 (0.03)

									122.72 (24.40)	
									169.47 (28.02)	
									0.73 (0.12)	
Rigoldi et al. (2012)	Cross-sectional	DS	48		N/A	N/A	S.T.		**DS**	
			12 DS	35.6 ±4.43				The % stance	63.1 (3.75)	59.65 (3.19)
			16 EDS	43.08 ±6.77				mean velocity (1/sec)	0.68 (0.17)*	1.12 (0.18)
			20 TD	40.1 ± 4.8				anterior step length	0.406*	0.88 (0.21)
							K.	**indexes (º)**		
								Pelvis		
								Mean value of pelvis tilt	17.54 (7.2)*	6.53 (6.97)
								Pelvis tilt range of motion	4.11 (2.95)	3.62 (0.86)
								Hip		
								Initial contact angle in sagittal plan	35.21 (11.84)	27.23 (9.57)
										43.52 (4.76)
								Flexion-extension range of motion	39.53 (8.88)	-14.83 (9.6)
									-2.33 (6.36)*	33.45 (6.89)
								Minimum of hip flexion in stance	38.93(10.36) *	
										4.39 (6.53)

	Maximum flexion during gait cycle	11 (7.57)*	57.08 (6.63)
		42.71 (16.1)*	0.12 (3.82)
	Knee		
			59.07 (6.31)
	Initial contact angle in sagittal plan	1.4 (6.45)	
		41.3 (12.49)*	1.81 (6.87)
	Maximum flexion during swing		
			21.04 (5.16)
	Minimum of knee flexion in stance		
		-0.12 (7.94)	-9.73 (9.40)
	Flexion-extention range of motion	14.05 (5.93)*	25.72 (6.56)
	Ankle		
Kn.		-1.82 (4.91)*	11.08 (7.32)
	Initial contact angle in sagitttal plan	10.08 (6.82)*	12.6 (9.18)
	Maximum dorsiflexion in stance		30.72 (8.75)
	Minimum dorsiflexion in stance		9.77 (5)
		17.86(10.84) *	
	Dorsi-plantarflexion ROM		
O.V.		2.22 (2.75)*	0.02 (0.007)
	Generated hip work (J/kg)	14.41 (6.9)*	0.083 (0.03)
	Absorbed hip work (J/kg)	8.72 (4.33)	
	Generated ankle work (J/kg)		
	Absorbed ankle work (J/kg)		

								Joint stiffness (Nm/kg degree)	0.016(0.006) *	
								Hip stiffness		
								Ankle stiffness	0.067 (0.02)*	
Agiovlasitis et al. (2011)	Cross-sectional Study	DS	36		N/A		S.T.	Preferred walking speed(m/s)	1.07(0.26)*	1.37(0.17)
			18 DS	24.7±6.8		8/10	En.	Resting metabolic rate	0.05(0.01)	0.04(0.01)
			18 TD	26.4±5.1		8/10		Speed at minimal gross energetic cost of transport (m/s)	1.01(0.11)*	1.20(0.11)
								Speed at minimal net energetic cost of transport (m/s)	0.87(0.12)	1.03(0.16)
Agiovlasities et al.(2011a)	Cross-sectional	DS	40		N/A		En.	Gross oxygen uptake	DS> C	
			18 DS	24.7±6.8		8/10				
			22 TD	25.9±4.8		9/13				
Rigoldi et al. (2011)	Longitudinal	DS	73		N/A	N/A		**Children**		
			32 DS	DS Children				Step length (mm/m)	0.63 (0.11)*	0.72 (0.09)
				9.2 ± 2.5			S.T.	Step width (mm/m)	0.22 (0.46)*	0.1 (0.01)
				DS Teens				Velocity (m/s)	1.03 (0.16)*	1.13 (0.12)
				16.7 ± 3.2						
				DS Adults				Hip initial contact angle		22.11 (7.98)
				37.3 ± 5.4			K.	Hip-ROM in sagittal plane		42.67 (5.71)

			Hip-ROM in frontal plane	34.48(6.77) *	10.75 (3.35)
41 C	TD Children		Knee-ROM in sagittal plane		49.64 (5.34)
	8.12 ± 2.6		Ankle initial contact angle	34.52(9.81) *	-1.9 (13.3)
	TD Teens		Ankle-ROM in sagittal plane		22.6 (6.58)
	18.03 ± 1.9		Shoulder-ROM in frontal plane	12.89 (4.4)*	8.54 (3.89)
	TD Adults			51.42(11.17)	
	37.6 ± 4.3		Hip power generation (mJ/kg)		15.5 (14.83)
		Kn.	Hip absorption (mJ/kg)	-4.01 (14.1)*	-5.8 (3)
			Knee absorption (mJ/kg)	23.51 (12.1)	-10.97 (4.7)
			Ankle power generation(mJ/kg)		30.4 (12.7)
			GRF in medio-lateral (%BW)	9.37 (4.81)	-5.98 (4.1)
			GRF in antero-posterior (%BW		15.9 (2.4)
			Teens	20.8 (9.23)*	
				-2.9 (3)*	
			Step length (mm/m)	-11.7 (9.7)	0.75 (0.06)
		S.T.	Step width (mm/m)		0.06 (0.02)
			Velocity (m/s)	13.6 (10.2)*	0.96 (0.07)
				-12.7 (3.2)*	
			Hip initial contact angle	10.9 (4.7)*	17.52 (7.5)

K.	Hip-ROM in sagittal plane		39.65 (4.32)
	Hip-ROM in frontal plane		10.92 (3.5)
	Knee-ROM in sagittal plane	0.63 (0.1)*	56.04 (3.65)
	Ankle initial contact angle	0.13 (0.04)*	1.25 (3.63)
	Ankle-ROM in sagittal plane	0.93 (0.01)*	23.25 (5.51)
	Shoulder-ROM in frontal plane		7.71 (2.8)
Kn.	Hip power generation (mJ/kg)	34.8 (8.33)*	13.55 (6.03)
	Hip absorption (mJ/kg)	38.78(10.42)	-11.79 (5.2)
	Knee absorption (mJ/kg)		-15.7 (9.58)
	Ankle power generation(mJ/kg)	13.09(4.09)*	34.21 (14.5)
	GRF in medio-lateral (%BW)	52.39	-6.22 (2.28)
	GRF in antero-posterior (%BW)	(10.76)*	20.97 (3.49)
	Adults	-2.13 (6.3)*	
	Step length (mm/m)	20.74(6.12)*	0.74 (0.07)
S.T.	Step width (mm/m)	11.37 (5.87)	0.07 (0.02)
	Velocity (m/s)		1.02 (0.09)

		28.81(22.6) *	
	Hip initial contact angle		27.23 (9.57)
		-3.3 (4.2)*	
K.	Hip-ROM in sagittal plane		43.89 (3.27)
		-11.9 (8.8)*	
	Hip-ROM in frontal plane		10.71 (3.06)
	Knee-ROM in sagittal plane	16.5 (12.2)*	58.28 (6.31)
	Ankle initial contact angle	-12.2 (3.9)*	1.13 (1.76)
	Ankle-ROM in sagittal plane	11.6 (4.8)*	24.69 (4.11)
	Shoulder-ROM in frontal plane		8.22 (2.63)
	Hip power generation (mJ/kg)	0.7 (0.1)	11.78 (7.26)
Kn.	Hip absorption (mJ/kg)	0.14 (0.02)*	-12.6 (9.8)
	Knee absorption (mJ/kg)		-15.49 (8.4)
	Ankle power generation (mJ/kg)	0.94 (0.11)*	30.72 (8.75)
	GRF in medio-lateral (%BW)		-4.64 (2.5)
	GRF in antero-posterior (%BW	32.07(9.17) *	19.34 (4.58)
		39.03(8.54) *	
		13.07(3.81) *	

									48.22(11)*	
									-5.35 (5.86)*	
									20.31(5.84) *	
									9.42 (2.97)	
									24.3 (10.7)*	
									-1.18 (1.1)*	
									-7.7 (3.7)*	
									16.6 (9.2)*	
									-11.6 (2.6)*	
									11.3 (4.8)*	
Smith et al. (2011)	Cross-sectional	DS	58		N/A	N/A		**New walkers**		
			9 DS New walker	17.5-46.5 mon.			S.T.	Stride length (m)	0.38 (0.04)	0.35 (0.05)
								Step width (m)	0.18 (0.03)	0.13 (0.03)
								Treadmill speed (m/sec)	0.52 (0.09)	0.52 (0.10)
			8 DS Preadol escents	8-10 yrs.						
								Preadolescents		

			12 DS Adults	35-62 yrs.			S.T.	Stride length (m)	0.68 (0.08)	0.91 (0.04)
								Step width (m)	0.14 (0.03)	0.08 (0.03)
			9 TD new walker	13-22.5 mon.				Treadmill speed (m/sec)	0.75 (0.06)	0.82 (0.10)
			8 TD preadolescents	8-10 yrs.				**Adults**		
							S.T.	Stride length (m)	0.62 (0.04)	1.03 (0.03)
			12 TD adults	35 – 54 yrs.				Step width (m)	0.14 (0.02)	0.09 (0.02)
								Treadmill speed (m/sec)	0.54 (0.17)	0.75 (0.16)
Mulvey et al. (2011)	Cross-sectional	DS	20		N/A			**1 month**		
			10 DS	2yr, 2mon		6/4	S.T.	Step length	17.91(4.94)	20.57 (2.52)
			10 TD	1yr,2.5mon		6/4		Step velocity	49.89 (22.56)	59.16(12.02)
								Step width	20.67 (4.22)	16.9 (2.03)
								3 month		
							S.T.	Step length	24.27 (4.89)	24.48 (2.94)
								Step velocity	76.01 (21.82	79.13 (18.42)
								Step width	18.11 (5.06)	11.22 (1.24)
								Overall		
							S.T.	Step length		22.53 (3.33)

								Step velocity	21.09 (5.77)	69.15 (18.22)
								Step width	62.95 (25.34)	13.66 (2.99)
									19.39 (4.69)	
Smith et al. (2010)	Cross-sectional	DS	28	35-65 years	N/A	N/A	S.T.	Stride length (m)	0.83 (0.07)	1.15 (0.09)
			14 DS					Stride frequency(s/stride)	0.79 (0.05)	0.81 (0.04)
			14 TD					Stride velocity(m/sec.)	0.67 (0.06)	0.95 (0.07)
								Step width (m)	0.13 (0.03)	0.09 (0.03)
								Percent stance (%)	71% (4%)	69% (4%)
Cimolin et al. (2010)	Cross-sectional	PWS	60		N/A				**DS**	
		DS	19 PWS	25.7 ± 6.1		11/8	S.T.	%Stance (% gait cycle)	60.95 (3.10)	59.45 (1.45)
			21 DS	25.7 ± 6.1		12/9		Anterior step length	0.28 (0.04)*	0.88 (0.21)
			20 TD	33.4 ± 9.6		10/ 10		Cadence (Step/min)	94.32 (11.24)*	111.80 (4.80)
								Velocity (m/s)	0.45 (0.08)*	0.78 (0.06)
							K.	**Pelvis (^{o})**		
								Mean pelvis tilt	18.01 (4.84)*	6.53 (6.97)
								Pelvic Obliquity-ROM	6.05 (2.12)	6.01 (2.53)
								Pelvis ROM in transversal plane	9.95 (2.69)	10.72 (5.32)

	Hip joint (º)		
	Initial contact angle	33.74 (11.46)*	27.23 (9.57)
	Minimum flexion in stance	1.32 (9.20)*	-14.83 (9.60)
	Flexion-extension ROM	32.42 (8.61)*	43.52 (4.76)
	Ab-aduction ROM	12.58 (4.21)	10.71 (3.06)
	Knee joint (º)		
	Initial contact angle	2.54 (7.75)	4.06 (6.63)
	Minimum flexion in stance	0.41 (8.09)	0.12 (3.82)
	Maximum flexion during swing	41.06 (10.68)*	58.01 (6.18)
	Flexion-extension ROM	43.81 (11.34)*	60.28 (6.31)
	Ankle joint and foot (º)		
	Initial contact angle	-3.55 (4.88)*	1.81 (5.87)
	Maximum dorsiflexion in stance	11.47 (4.26)*	21.04 (5.16)
	Minimum dorsiflexion in stance	-2.94 (3.91)*	-8.74 (9.40)
	Dorsi-plantar ROM	14.41 (3.77)*	27.72 (6.56)
	Maximum dorsiflexion in swing	6.15 (4.40)	8.63 (9.93)
Kn.	Maximum ankle power during terminal stance		3.07 (0.86)

	Normalized Maximum ankle power during terminal stance	1.35 (0.64)	2.42 (3.06)
		2.02 (0.86)	
	Hip stiffness: Kh index		
O.V.			0.03
	Ankle stiffness: Ka index		
			0.1
		0.06*	
	%Stance (% gait cycle)		
S.T.		0.06*	
	Anterior step length		
		PWS	
	Cadence (Step/min)		
		63.88 (9.12)*	
	Velocity (m/s)		
		0.33 (0.04)*	
		111.76 (9.12)	
	Pelvis (º)		
K.		0.63 (0.10)*	
	Mean pelvis tilt		
	Pelvic Obliquity-ROM		
	Pelvis ROM in transversal plane		
		20.86 (8.84)*	
	Hip joint (º)		
		8.46 (3.36)*	
	Initial contact angle		
		10.95 (3.61)	
	Minimum flexion in stance		
	Flexion-extension ROM		

	Ab-aduction ROM	45.88 (12.82)*
	Knee joint (º)	
	Initial contact angle	1.52 (10.66)*
	Minimum flexion in stance	45.37 (5.99)
	Maximum flexion during swing	16.89 (3.95)*
	Flexion-extension ROM	
	Ankle joint and foot (º)	8.42 (6.64)*
	Initial contact angle	-2.58 (5.92)
	Maximum dorsiflexion in stance	53.25 (7.61)*
	Minimum dorsiflexion in stance	55.83 (8.05)*
	Dorsi-plantar ROM	
	Maximum dorsiflexion in swing	-3.15 (9.24)*
		14.80 (8.81)*
		-10.25 (8.79)
Kn.	Maximum ankle power during terminal stance	25.16 (3.38)
	Normalized Maximum ankle power during terminal stance	13.77 (9.03)*
		1.96 (0.56)
	Hip stiffness: Kh index	
O.V.	Ankle stiffness: Ka index	

									2.05 (0.49)	
									0.02	
									0.06*	
Hocking et al. (2010)	Cross-sectional	WS	27		N/A			**Preferred walking**	**DS**	
		DS	9 WS	25.1 ±5.2		5/4	S.T.	Speed (cm/s)	106.1 (29.3)*	141.0 (7.0)
			9 DS	28.8 ±5.8		3/6		Cadence (steps/min)	108.1 (20.8)	112.5 (3.8)
			9 TD	24.3 ±3.1		3/6		Stride length (cm)	112.3 (20.0)*	150.47 (7.1)
								Double support (% gait cycle)	24.8 (5.0)	20.3 (3.1)
								Base of support (cm)	12.3 (4.3)	7.8 (2.2)
								Baseline intra-individual variability		
							S.T.	Speed	5.3 (3.4)	1.8 (0.2)
								Stride time	3.6 (2.0)	1.4 (0.3)
								Stride length	3.5 (2.7)	1.1 (0.2)
								Double support	8.7 (1.2)	7.6 (1.9)
								Base of support	21.4 (11.1)	19.3 (4.4)

								Preferred walking		
							S.T.	Speed (cm/s)	**WS**	
								Cadence (steps/min)	122.8 (26.4)	
								Stride length (cm)	119.0 (13.0)	
								Double support (% gait cycle)	123.8 (22.5)*	
								Base of support (cm)	22.5 (3.7)	
								Baseline intra-individual variability	11.5 (1.7)*	
							S.T.	Speed		
								Stride time		
								Stride length	2.8 (1.3)	
								Double support	2.2 (1.2)	
								Base of support	2.3 (1.7)	
									9.0 (3.0)	
									16.4 (5.5)	
Mendonca et al. (2010)	Cross-sectional	DS	34 18 DS 16 TD	 33.6 ± 7.6 33.3 ± 8.0	N/A	 14/4 12/4	En.	peak exercise oxygen uptake (mL . kg − 1 .min − 1) peak exercise heart rate (bpm) Peak exercise respiratory exchange ratio	29.1 ± 6.3 * 159.0 ± 16.6* 1.19 ± 0.17*	46.9 ± 10.6 185.2 ± 10.9 1.37 ± 0.13

								peak exercise minute ventilation (L . min − 1)	61.0 ± 17.6*	123.0 ± 33.2
Agiovlasitis et al. (2009)	Cross-sectional	DS	30		N/A		En.	Net rate of oxygen uptake	DS>C	
			15 DS	27.7±7.5		8/7		Net oxygen uptake per kilometer	DS>C	
			15 TD	28.2±5.7		8/7				
Black et al. (2009)	Longitudinal	DS	16		N/A			Over-ground Comfortable walk		
			8 DS	116.3 (28.93) weeks		4/4	S.T.	**0 months of walking experience**		
								Dimensionless step width	0.7 (0.15)	0.6 (0.06)
			8 TD	60.3 (9.70) weeks		5/3		dimensionless stride length	0.8 (0.36)	0.8 (0.29)
								Dimensionless frequency	0.2 (0.06)	0.2 (0.03)
								Dimensionless speed	0.2 (0.09)	0.1 (0.06)
								% stance time	0.6 (0.12)	0.7 (0.12)
								% double support time	0.3 (0.20)	0.4 (0.14)
							S.T.	**1 months of walking experience**	0.6 (0.12)	0.6 (0.10)
								Dimensionless step width	1.1 (0.46)	1.4 (0.19)
								dimensionless stride length	0.2 (0.03)	0.2 (0.03)
								Dimensionless frequency	0.3 (0.14)	0.3 (0.07)
								Dimensionless speed	0.6 (0.06)	0.6 (0.03)

	% stance time	0.2 (0.10)	0.2 (0.05)
	% double support time		
S.T.	**3 months of walking experience**	0.6 (0.17)	0.4 (0.09)
		1.4 (0.25)	1.7 (0.28)
	Dimensionless step width		
		0.2 (0.03)	0.3 (0.02)
	dimensionless stride length		
		0.4 (0.08)	0.5 (0.10)
	Dimensionless frequency		
		0.6 (0.3)	0.6 (0.04)
	Dimensionless speed		
		0.2 (0.04)	0.2 (0.05)
	% stance time		
	% double support time		
S.T.		0.5 (0.15)	0.3 (0.09)
	4 months of walking experience	1.5 (0.29)	1.6 (0.35)
		0.3 (0.05)	0.3 (0.04)
	Dimensionless step width		
		0.4 (0.13)	0.5 (0.15)
	dimensionless stride length		
		0.6 (0.03)	0.5 (0.03)
	Dimensionless frequency		
		0.2 (0.05)	0.1 (0.04)
	Dimensionless speed		
	% stance time		
S.T.		0.4 (0.09)	0.3 (0.08)
	% double support time		
		1.4 (0.37)	1.7 (0.18)
	6 months of walking experience	0.3 (0.05)	0.3 (0.07)

	Dimensionless step width	0.4 (0.15)	0.5 (0.14)
	dimensionless stride length	0.6 (0.04)	0.5 (0.05)
	Dimensionless frequency	0.1 (0.04)	0.1 (0.04)
	Dimensionless speed		
	% stance time		
	% double support time		
	% over-ground walk	0.570 (0.129)	0.367 (0.097)
S.T.	40%	0.744 (0.219)	0.746 (0.217)
	4 months of walking experience	0.253 (0.036)	0.261 (0.036)
		0.179 (0.055)	0.188 (0.044)
	Dimensionless step width		
	Dimensionless stride length		
		0.473 (0.107)	0.319 (0.081)
	Dimensionless frequency		
S.T.		0.791 (0.162)	0.823 (0.224)
	Dimensionless speed		
		0.280 (0.030)	0.263 (0.059)
	6 months of walking experience	0.215 (0.023)	0.209 (0.045)
	Dimensionless step width		
	Dimensionless stride length		
		0.470 (0.067)	0.348 (0.092)
	Dimensionless frequency		

S.T.	Dimensionless speed	1.355 (0.248)	1.169 (0.274)
	75%	0.292 (0.014)	0.293 (0.036)
	4 months of walking experience	0.395 (0.090)	0.340 (0.084)
	Dimensionless step width	0.457 (0.062)	0.312 (0.091)
S.T.	Dimensionless stride length	1.244 (0.156)	1.362 (0.270)
	Dimensionless frequency	0.297 (0.031)	0.287 (0.025)
	Dimensionless speed	0.368 (0.062)	0.389 (0.077)
	6 months of walking experience		
	Dimensionless step width		
	Dimensionless stride length	0.422 (0.007)	0.342 (0.105)
S.T.	Dimensionless frequency	1.773 (0.499)	1.448 (0.162)
	Dimensionless speed	0.329 (0.022)	0.343 (0.010)
	110%	0.588 (0.202)	0.495 (0.068)
	4 months of walking experience		
		0.436 (0.114)	0.281 (0.077)
S.T.	Dimensionless step width	1.503 (0.115)	1.680 (0.261)
	Dimensionless stride length	0.318 (0.060)	0.323 (0.035)
	Dimensionless frequency	0.472 (0.052)	0.542 (0.106)

								Dimensionless speed		
								6 months of walking experience		
								Dimensionless step width		
								Dimensionless stride length		
								Dimensionless frequency		
								Dimensionless speed		
Agiovlasitis et al. (2009)	Cross-sectional	DS	30		N/A		S.T.	Step width	DS=C	
			15DS	19-44yr		8/7		Step length	DS<C	
			15 TD	18-42yr		8/7		Step time	DS<C	
							O.V	COM 3D	DS= C	
								Mediolateral COM	DS> C	
								Vertical COM	DS=C	
								Anteroposterior COM	DS=C	
Hocking et al. (2009)	Cross-sectional	WS	18		WS			**Preferred**		
			9 WS	24.2 ±5.5	experience mild to moderate	6/3	S.T.	Speed (cm/sec)	117.4 (27.4)	144.0 (8.8)

9 TD	24.7 ±3.5	intellectual impairment	6/3		Cadence (steps/min)	117.7 (12.8)	113.1 (3.6)
					Stride length (cm)	119.7 (22.6)*	152.8 (8.8)
					Double support (% gait cycle)	21.5 (3.6)	18.5 (7.2)
					Base of support (cm)	12.8 (4.1)	8.6 (2.8)
				S.T.	**Slow**		
					Speed (cm/sec)	85.0 (21.8)	99.2 (13.7)
					Cadence (steps/min)	98.7 (8.7)	92.9 (9.4)
					Stride length (cm)	103.4 (25.3)	128.0 (9.4)
					Double support (%gait cycle)	22.6 (3.8)	24.4 (2.4)
					Base of support (cm)	13.2 (4.7)	9.5 (3.4)
				S.T.	**Fast**		
					Speed (cm/sec)	150.7 (29.8)	179.9 (17.6)
					Cadence (steps/min)	134.8 (13.1)	125.0 (7.9)
					Stride length (cm)	134.2 (22.3)*	172.6 (10.9)
					Double support (% gait cycle)	20.0 (2.9)	18.4 (2.0)
					Base of support (cm)	12.9 (4.9)	9.0 (2.6)

Chiba et al. (2009)	Longitudinal	ID	75 38 Fallers 37 non-fallers	30-69 yrs	Mod. 4 Sev. 14 Pro. 19 Mod.7 Sev.19 Pro. 16	17/21 16/21	S.T.	Walking speed (m/sec) Step length (m/step) Walking speed (m/sec) Step length (m/step)	**Fallers** .69 (.03) .39 (0.12) **Non-fallers** .991 (0.28) 0.49 (0.12)	N/A
Rigoldi et al (2009)	Cross-sectional	DS	19 9 DS 10 TD	Children (age not specified)	N/A	N/A	K.	Pelvic tilt in sagittal plane Hip angle Hip range of motion Knee angle during stance Maximum knee angle during swing	**Most functional gait** ≈ C Mild flexed ≈ C Slightly flexed ≈ C Decreased	N/A

Kn.	Ankle dorsi-plantar flexion range of motion during gait cycle	=C
	Dorsi-plantar flexion moment peak during terminal stance	DS< C
	Ankle generated power	**Least functional gait**
K.		Highest
		More flexed
	Pelvic tilt in sagittal plane	Limited
	Hip angle	Worse than most functional
	Hip range of motion	Prolonged
	Knee range of motion	
		Decreased
Kn.	Ankle plantarflexion	Lowest value in DS group
	Dorsi-plantar flexion moment peak	
	Ankle generated power	

Gontijo et al. (2008)	Longitudinal	DS	24		N/A			**0 walking experience**		
			12 DS	103.9(18.9) weeks		5/7	Kn.	Gravitational torque stance	65.30(10.9)	58.76(8.29)
								Gravitational torque swing	3.04(1.25)	2.83(0.49)
			12 TD	52.1 (5.29) weeks		6/6	D.E.	normalized co-contraction indices (CCL/mLg)	DS>C	
								15 days experience		
							Kn.	Gravitational torque stance	66.17(10.04)	61.96(7.33)
								Gravitational torque swing	3.23(0.86)	2.95(0.63)
							D.E.	normalized co-contraction indices (CCL/mLg)	DS>C	
								30 days experience		
							Kn.	Gravitational torque stance	66.39(8.62)	64.33(6.06)
								Gravitational torque swing	3.37(0.84)	3.01(0.39)
							D.E.	normalized co-contraction indices (CCL/mLg)	DS>C	
								60 days experience		

	Gravitational torque stance		
Kn.	Gravitational torque swing	70.08(9.74)	66.22(6.44)
	normalized co-contraction indices (CCL/mLg)	3.46(0.79)	3.23(0.43)
D.E.		DS>C	
	90 days experience		
	Gravitational torque stance		
	Gravitational torque swing		
Kn.		71.52(9.58)	68.63(7.07)
	normalized co-contraction indices (CCL/mLg)	3.62(0.80)	3.36(0.50)
D.E.		DS>C	
	normalized co-contraction indices (CCI/mLg) Swing		
D.E.	Total		
	Hip		
	Knee	DS>C *	
	Ankle	DS>C*	
		DS>C*	
		DS=C	

Galli et al. (2008)	Cross-sectional	DS	128		N/A	N/A				
			98 DS	11.7 yrs.			S.T.	Gait speed	0.42(0.08)*	0.85(0.06)
			30 TD	11 yrs.				Stride length	0.29(0.04)*	0.89(0.09)
									37.0(8.1)	29.0(5.2)
									11.5(9.7)	-6.6(6.4)
							K.	Hip flexion at initial contact (º)		
									27.4(7.1)	37.9(4.1)
								Hip max. extension in stance (º)		
									10.3(7.0)	6.3(4.7)
								Hip range of motion in sagittal(º)	14.7(9.3)	6.5(4.2)
								Knee flexion at initial contact(º)	A reduction	
								Knee flexion at mid stance(º)	Reduced	
								Knee flexion in swing(º)	-4.6(9.3)	-9.9(10.1)
								Ankle first rocker plantarflexion(º)	0.7(0.3)	0.3±0.4
								Ankle peak plantarflexionat toe-off (º)		
									Increased	
							Kn.		-0.1(0.2)	0.8(0.2)
								Hip maximum flexor moment at initial contact m/kg	0.9(0.3)	1.3(0.4)
								Hip extensor moment at stance	1.8(0.3)	3.2(0.8)
								Knee first extensor moment peak		

								Ankle moment maximum index		
								Power generating capacity at push of	0.058(0.025) *	0.028(0.007)
										0.103(0.014)
									0.058(0.05)*	
							O.V.			
								Joint stiffness		
								Hip stiffness (N m)/(kg degree)		
								Ankle stiffness (N m)/(kg degree)		
Smith & Ulrich (2008)	Cross-sectional	DS	24		N/A		S.T.	Stride length (m)	0.75 (0.17)*	1.13 (0.15)
			12 DS	43.33 ±8.35		6/6		Dimensionless stride length	1.09 (0.23)*	1.54 (0.2)
			12 TD	44.83 ±7.04		1/11		Step width (m)	0.16 (0.04)*	0.11 (0.03)
								Dimensionless step width	0.23 (0.06)*	0.15 (0.04)
								Velocity (m/s)	0.63 (0.2)*	0.99 (0.21)
								Dimensionless velocity	0.24 (0.08)*	0.37 (0.08)
								Stride frequency (Hz)	0.82 (0.15)	0.87 (0.1)
								Dimensionless frequency	0.22 (0.04)	0.24 (0.03)
								Percent stance	0.67 (0.05)*	0.63 (0.03)
								Percent double support	0.33 (0.09)*	0.26 (0.05)
Vismara et al. (2007)	Cross-sectional	PWS	53		N/A					
			19 PWS	25.7 ± 6.1		11/9	S.T.	Cadence (steps/min)		117.84 (4.80)

	14obese 20 TD	29.4 ± 7.9 30.2 ± 5.2	5/9 10/10		Stance (% gait cycle)	111.76(9.12)*	60.07 (1.40)
					Single Support (% gait cycle)		39.91 (1.48)
					Normalized Stride Length	63.88 (2.47)*	0.80 (0.04)
					Normalized Walking Speed (m/sec)	35.81 (3.94)*	0.78 90.06)
						0.67 (0.07)*	
				K.	Hip-ROM in sagittal plane (°)	0.63 (0.09)*	45.92 (3.25)
					Knee-ROM in sagittal plane (°)		61.23 (4.02)
					Ankle-ROM in sagittal plane (°)		31.90 (4.81)
					Peak of ankle plantarflexion (°)	46.19(5.4)	-18.98 (6.19)
					Peak of ankle dorsiflexion in swing(°)	56.11(8.24)*	4.19 (3.53)
					Foot progreassion (°)	25.06 (3.65)*	-6.88 (3.96)
						-8.31 (5.87)*	
				Kn.	Peak of plantarflexion moment (N s/ kg)	15.63 (6.59)*	1.13 (0.13)
					Peak of ankle generated power (W s/ kg* m)		2.57 (0.4)
						-16.64 (8.92)*	

									1.07 (0.22)*	
									1.95 (0.53)*	
Marchewka & Chwala (2007)	Cross-sectional	DS	10 DS	17.8±2.69	IQ 37.6±4.29	9/1	S.T.	Left Leg		N/A
								Step length (m)	0.39(0.12)	
								Cadence (steps/min)	103(25.3)	
								Speed(m/sec)	0.68(0.29	
								Single support(sec)	0.44(0.11)	
								Double support(sec)	0.44(0.43)	
								Right leg		
								Step length (m)	0.39(0.13)	
								Cadence (steps/min)	102(25.4)	
								Speed(m/sec)	0.68(0.29)	
								Single support(sec)	0.43(0.091)	
								Double support(sec)	0.47(0.49)	
Smith et al. (2007)	Cross-sectional	DS	16	8-10 yrs.	N/A	N/A		**Over-ground walk**		
			8 DS				S.T.	Stride length (m)	0.91 (0.15)	1.12(0.14)
			8 TD					dimensionless stride length	1.63	1.67

	step width (m)	0.12(0.04)	0.08(0.03)
	dimensionless step width	0.22	0.11
	stride frequency (Hz)	1.09(0.15)	0.97(0.07)
	dimensionless stride frequency	0.26	0.25
	gait speed (m/sec.)	1.01(0.10)	1.08(0.14)
	dimensionless gait speed	0.43	0.42
	Treadmill walk		
S.T.	**40%** over-ground speed		
	Stride length (m)	0.43(0.06)	0.56 (0.10)
	dimensionless stride length	0.76	0.83
	step width (m)	0.15(0.02)	0.08 (0.03)
	dimensionless step width	0.27	0.13
	stride frequency (Hz)	1.02(0.21)	0.81 (0.10)
	dimensionless stride frequency	0.24	0.21
	gait speed (m/sec.)	0.40(0.03)	0.43 (0.06)
	75% over-ground speed		

								Stride length (m)	0.68(0.09)	0.89 (0.09)
								dimensionless stride length	1.22	1.31
								step width (m)	0.14(0.02)	0.08 (0.03)
								dimensionless step width	0.25	0.12
								stride frequency (Hz)	1.17(0.15)	0.93 (0.07)
								dimensionless stride frequency	0.28	0.25
								gait speed (m/sec.)	0.75(0.06)	0.82 (0.10)
								110% over-ground speed		
								Stride length (m)	0.83(0.09)	1.11 (0.11)
								dimensionless stride length	1.54	1.68
								step width (m)	0.13(0.02)	0.07 (0.02)
								dimensionless step width	0.23	0.11
								stride frequency (Hz)	1.29(0.12)	1.1 (0.06)
								dimensionless stride frequency	0.31	0.28
								gait speed (m/sec.)	1.09(0.09)	1.20 (0.15)
Black et al. (2007)	Cross-sectional	DS	16	8-10 yrs.	N/A		O.V.	Variability for COM at heel contact in anterio-posterior direction	DS> C*	
			8 DS			5/3				
			8TD			5/3			DS> C*	

								Variability of head position at heel contact in anterio-posterior direction		
Kubo & Ulrich (2006)	Cross-sectional	DS	22 12 DS 10 TD	8-10 yrs.	N/A	N/A	S.T	**40%** over-ground speed		
								Normalized walking Speed	0.18(0.02)	0.19(0.04)
								Normalized Stride length	0.82(0.11)	1.00(0.18)
								Normalized Step width	0.40(0.07)	0.19(0.10)
								75% over-ground speed		
								Normalized walking Speed	0.34(0.05)	0.36(0.06)
								Normalized Stride length	1.26(0.16)	1.50(0.20)
								Normalized Step width	0.36(0.07)	0.18(0.09)
								110% over-ground speed		
								Normalized walking Speed	0.51(0.07)	0.35(0.09)
								Normalized Stride length	1.59(0.24)	1.89(0.26)
								Normalized Step width	0.29(0.09)	0.17(0.06)
								nO pelvis amplitude	DS> C	
								nO pelvis amplitude A-P	DS=C	
								nO pelvis amplitude M-L	DS>C*	
								nCOM HAT amplitude	DS>C	

								R AMP	DS>C	
Looper et al. (2006)	Longitudinal	DS	35 NW: 6DS 9 TD TT: 10DSl 10DSh	Toddlers	N/A	N/A	S.T.	Coefficient of variation for step length Coefficient of variation for step width	DS>C* DS>C*	
Ohwada et al. (2005)	Cross-sectional	ID	46 23 ID 23 TD	 36.3±8.9 36.3±8.0	IQ 35.5±10.3 N/A	 23/0 23/0	En	**Walking speed 30m/min** Oxygen consumption (ml/kg/min) Heart rate (beats/min) Number of steps per minute **Walking speed 50m/min** Oxygen consumption (ml/kg/min) Heart rate (beats/min) Number of steps per minute **Walking speed 70m/min**	9.27(1.44)* 85.8(14.4)* 86.1(11.6)* 11.33(2.15)* 93.0(15.6)* 106.3(10.3)* 13.40(2.35) 101.6(19.1)*	8.35(0.96) 74.5(10.1) 76.0(10.2) 10.08(1.54) 79.6(10.3) 98.5(8.1) 13.02(2.13) 86.8(9.0)

								Oxygen consumption (ml/kg/min)	120.2(9.2)*	112.0(10.1)
								Heart rate (beats/min)		
								Number of steps per minute		
Buzzi & Ulrich (2004)	Cross-sectional	DS	16	8.75±0.86	N/A	N/A	K.	**LyE**		
			8 DS					Shank	DS>C	
			8 TD					Thigh	DS>C	
								feet	DS>C	
							S.T.	**ApEn**		
								Shank	DS=C	
								Thigh	DS>C	
								Feet	DS>C	
Ulrich et al. (2004)	Cross-sectional	DS	24	8-10 yrs.	N/A			**Raw variables**		
			12 DS			8/4	S.T.	Speed (m/s)	1.04 (0.14)*	1.23 (0.18)
			12 TD			5/7		Stride frequency (Hz)	1.13 (0.09)	1.07 (0.12)
								Stride length (m)	0.92 (0.11)*	1.16 (0.10)
								Step width (cm)	11.73 (3.68)*	8.40 (1.66)
								% Stance phase	59.12 (2.36)	58.56 (1.64)

								% Double support phase	18.30 (4.94)	17.55 (3.07)
								Dimensionless variables		
								Speed	0.46 (0.06)	0.50 (0.08)
								Stride frequency	0.26 (0.02)	0.27 (0.03)
								Stride length	1.74 (0.18)	1.83 (0.24)
								Step width	0.22 (0.07)*	0.13 (0.03)
							O.V.	Dimensionless global stiffness of over-ground walk	5.068(0.589)	5.029(0.808)
								Dimensionless impulse of over-ground walk	0.856(0.165) *	0.604(0.151)
Cioni et al. (2001)	Cross-sectional	DS	27		IQ range		S.T.	Stride (sec)	1.3(.2)	1.3(.2)
			17DS	8-36 yrs.	(50-70)	13/4		Stance (sec)	.8(.2)	.8(.1)
			10 TD	8-30 yrs	N/A	7/3		Swing (sec)	.5(.8)	.5(.5)
								Swing (%)	35.6(4.4)	38.3(3.1)
								Cadence(steps/min.)	94.4(15.1)	96.5(12.4)
								Velocity (m/s)	.7(.3)	1.0(.2)
							K.	**.6-.9 m/sec.**		

								Dorsal flexion(°)	8.8(5.3)	8.0(4.2)
								Plantar flexion during terminal stance(°)	11.4(6.3)*	16.1(4.9)
								.9-1.2 m/sec.		
								Dorsal flexion(°)	9.9(5.0)	8.8(4.2)
								Plantar flexion during terminal stance (°)	11.4(9.0)*	16.2(10.6)
							Kn.			
								.6-.9 m/sec.		
								Moment of force (Nm/ Kg.m)	.7(.1)	.7(.1)
								Ankle peak power A1 (W/Kg.m)	-.4(.2)	-.5(.2)
								Ankle peak power A2(W/Kg.m)	-.5(.2)	1.0(.4)
								.9-1.2 m/sec.		
								Moment of force(Nm/ Kg.m)	.7(.1)	.9(.1)
								Ankle peak power A1(W/Kg.m)	.4(.1)	-.6(.3)
								Ankle peak power A2(W/Kg.m)	1.0(.4)	1.5(.2)
Gretz et al. (1998)	Cross-sectional	DS	41		N/A		S.T	Step length/leg length ratio	0.75(0.10)	0.78(0.04)
			21 DS	41±8 yrs.		9/12		Cycle time(sec.)	1.06(0.17)	1.11(0.11)
			20 TD	40±10 yrs.		9/11		Step time (sec.)	0.53(0.08)	0.55(0.05)

								Normalized velocity	1.46(0.34)	1.42(0.14)
								Single support(% gait cycle in single support)	37.3(1.8)	36.1(1.4)
								Double support (% gait cycle in double support)	24.7(3.8)	27.4(2.5)
								Base of support (cm)	12.04(3.74)	9.72(2.89)
								Left toe in/out (°)	6.9(5.8)	5.9(0.2)
							K.	Right toe in/out (°)	9.5(6.2)	7.2(4.5)
Sparrow et al. (1998)	Cross-sectional	ID	32		IQ		S.T	**Males**		
			16 ID	M 33.30 ±8.70 F 42.0 ±10.0	60.3	7/9		Relative Speed (stat/s)	ID> C	
								Walking speed (m/s)	ID>C	
								Stride Length (m)	ID<C	
			16 TD	M 34.90± 8.0 F 40.1± 11.6	N/A	7/9		Stride duration (s)	ID<C	
								Cadence (step/min)	ID>C	
								Stance as percentage of stride duration (%)	ID=C	
								Females		
								Relative Speed (stat/s)	ID> C	

								Walking speed (m/s)	ID>C	
								Stride Length (m)	ID<C	
								Stride duration (s)	ID<C	
								Cadence (step/min)	ID>C	
								Stance as percentage of stride duration (%)	ID=C	
Kim et al. (1995)	Cross-sectional	DS	25		N/A		S.T.	Stride length (cm)	72.8 cm	DS < C
			15DS	10.9 yrs		7/8		Velocity (cm/sec.)	69.8	DS <C
			10 TD	N/A		N/A		cadence(steps/min.)	114	Not significant
							K.	pelvic span to ankle spread ratio	0.48	DS > C
								Anterior pelvic tilt		DS > C
								Pelvic obliquity		DS > C
								Pelvic rotation		DS > C
								External rotation of foot		DS > C
							Kn.	Internal moment of hip flexion		DS < C
								power generation at hip joint		DS < C

								Power generation at ankle joint		DS < C
Accardo & Whitman (1989)	Longitudinal	ID	799					Toe walking	The presence of toe walking is evident in 35.8% of subjects with intellectual disability	
Parker & Bronks (1980)	Cross-sectional	DS	6 DS	7 yrs.	N/A	N/A	S.T. K.	% swing phase % stance phase **Hip** Maximum extension in stance (º) Maximum flexion during swing (º)	36% 64% 87 58	N/A

					Knee Initial contact average flexion(°) Flexion-extension ROM(°) **Ankle** Initial contact average extension(°) Shoulder rotation(°) Elbow Excursion (°) Out-toeing right foot(°) Out-toeing left foot(°)	7 65 103 65 26 17.2 25.75	
Lydic (1979)	Cross-sectional	DS	Children	N/A		34.7% displayed one or more abnormal patterns of movement: wide-based walking, external rotation of the hips, waddling from side to side.	N/A

TD: typical development; ID: intellectual disability; PWS: Prader-Willi syndrome; WS: Williams syndrome; EDS: Ehlers-Danlos syndrome; DS: Down syndrome; DSI: Down syndrome group with low intensity training; DSh: Down syndrome group with high intensity training; ApEn: Approximate Entropy-Regularity pattern of successive step lengths and widths; LyE: Lyapunov Exponent-Local Stability of Limb Trajectories Across Successive Strides; CCI: co-contraction indices; COM 3D: General patterns of center of mass three dimensional walking; nO pelvis amplitude: normalized midpoint of the two hip markers amplitudes; nCOM HAT amplitude: normalized center of mass head arms trunk amplitude; R AMP: Amplitude ratio; (Nm/Kg.m): Newton meters per kilogram; (W/Kg.m): Watts per kilogram meters; ROM: range of motion; GRF: ground reaction force; En. : energetic; S.T.: Spatial-Temporal; K.: Kinematics; Kn. : Kinetics ; D.E.: dynamic electromyography ; O.V.: other variable; N/A: not available **;** yrs.: years **;** M: male **;** F: female **;** IQ: Intelligence Quotient **;** N: number ; NW: new walkers ; TT: treadmill training; *M(SD):* mean (standard deviation) with significance indicated by *

Table 2. Studies reporting negotiating obstacles and walking under perturbed conditions.

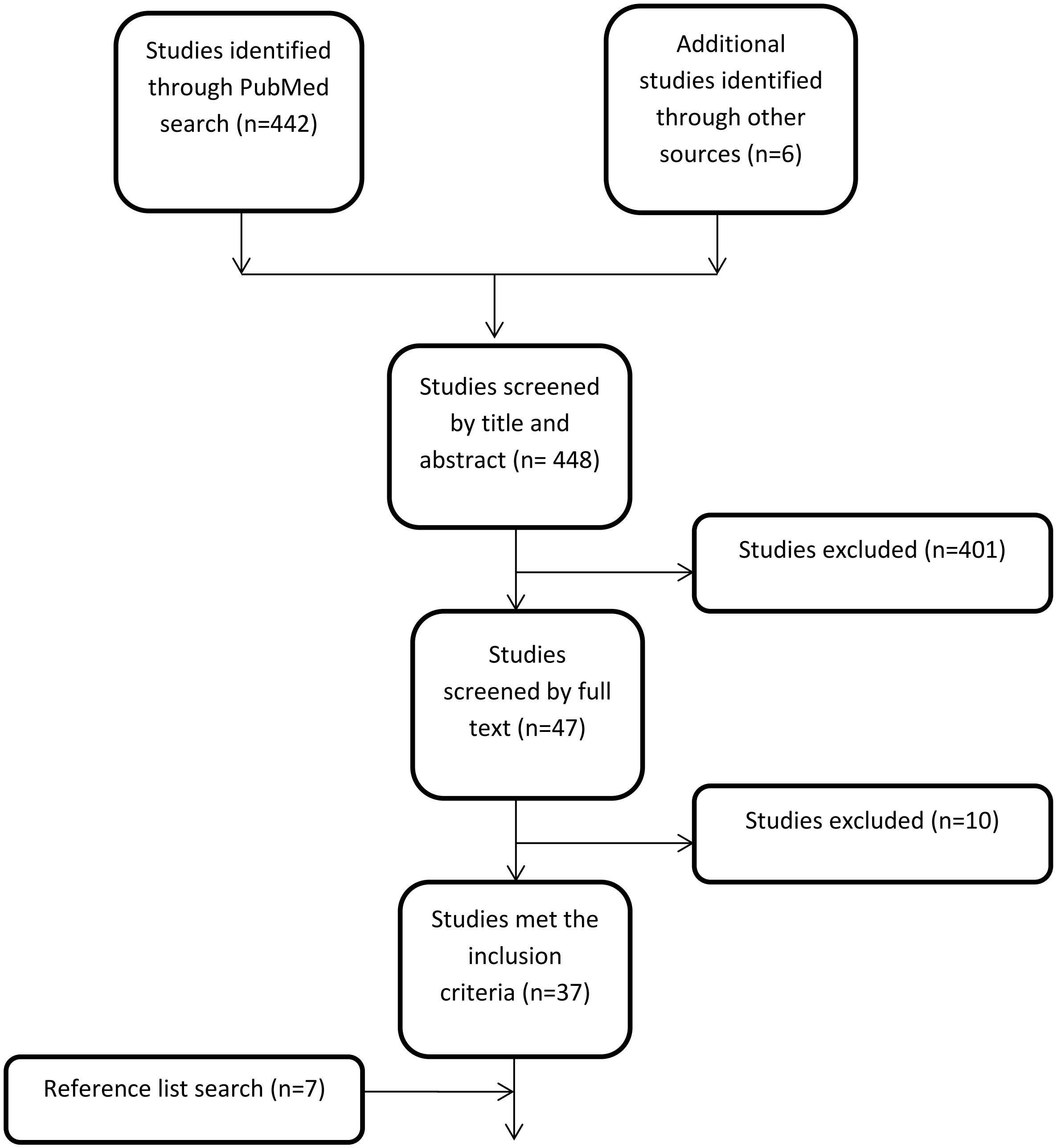
Study	Design	Population	N	Age	ID level	Sex M/F	Walking condition
Vimercati et al. (2013)	Cross sectional study	DS	26 10 DS 16 TD	 22±6 25±3	 56(12)	N/A	• Obstacle at ground level • Obstacle at a higher level, 10% of subject height
Hocking et al. (2011)	Cross-sectional study	DS WS	29 9 DS 10 WS	 28.8±5.8 24.6±5.2	 56.7±6.1 62.1±9.1	 3/6 6/4	• Obstacle at a higher level, 10% of subject's leg length

			10 TD	24.8±3.3	N/A	4/6	
Mulvey et al (2011)	Longitudinal study	DS	20 10 DS 10 TD	 2yrs 2months 1yr 2.5 months	N/A	 6/4 6/4	• A padded metal pipe obstacle, 4.75 cm high, 3.55m long
Smith et al. (2010)	Cross-sectional study	DS	28 14 DS 14 TD	35-65 yrs.	N/A	N/A	• Perturbation conditions — Divided attention-counting while walking — Distracting sounds — Irregular surface — Low light condition — Two combination conditions • Obstacle made of blue construction paper 83 cm wide, 8 cm high, 4cm long
Smith & Ulrich (2008)	Cross-sectional study	DS	24 12 DS 12 TD	 43.33±8.35 44.83±7.04	N/A	 6/6 1/11	• Obstacle: A foam covered rod 14 cm circumference, 12cm above and perpendicular to the walkway.
Sparrow et al. (1998)	Cross-sectional study	ID	32 16 ID	 M 33.30 ±8.70	IQ 60.3	 7/9	• Obstacle, metal rod: set at 10%, 25%, and 40% of leg length • Obstacle, tapes attached to the floor

		F 42.0 ±10.0		
	16 TD	M 34.90± 8.0	N/A	7/9
		F 40.1± 11.6		

DS: Down syndrome; TD: Typical Development; WS: Williams syndrome; ID: intellectual disability; IQ: Intelligence Quotient; N/A: not available;

Figure 1 Flow diagram of data selection process



Studies included for final review (n=44)